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SOLAR PHYSICS AND THE SOLAR-STELLAR CONNECTION AT DOME C

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Abstract. Solar magnetic fields evolve on many time-scales, *e.g.*, the generation, migration, and dissipation of magnetic flux during the 22-year magnetic cycle of the Sun. Active regions develop and decay over periods of weeks. The build-up of magnetic shear in active regions can occur within less than a day. At the shortest time-scales, the magnetic field topology can change rapidly within a few minutes as the result of eruptive events such as flares, filament eruptions, and coronal mass ejections. The unique daytime seeing characteristics at *Dome C*, *i.e.*, continuous periods of very good to excellent seeing during almost the entire Antarctic summer, allow us to address many of the top science cases related to the evolution of solar magnetic fields. We introduce the *Advanced Solar Photometric Imager and Radiation Experiment* and present the science cases for synoptic solar observations at *Dome C*. Furthermore, common science cases concerning the solar-stellar connection are discussed in the context of the proposed *International Concordia Explorer Telescope*.

1 Introduction

Ground-based solar physics is currently seeing vigorous efforts to upgrade existing facilities and to develop the next generation of telescopes and instruments. These efforts are not restricted to telescopes with large apertures (1.5 to 4 m) for high-resolution observations of solar fine-structure but also include synoptic instruments and special purpose telescopes such as coronagraphs.

Several major solar telescope are currently being build *e.g.*, the *New Solar Telescope* (NST) at Big Bear Solar Observatory (BBSO) in California (Denker *et al.* 2006) and the German *GREGOR* project at Observatorio del Teide on Tenerife, Spain (Volkmer *et al.* 2006). The *Advanced Technology Solar Telescope* (ATST, Wagner *et al.* 2006) under the stewardship of the U.S. National Solar Observatory (NSO) is in the final stages of the design and development phase awaiting funding approval for construction at Mees Solar Observatory (MSO) on Maui, Hawai'i. The current suite of synoptic telescopes includes

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the six *Global Oscillation Network Group* (GONG, Harvey *et al.* 1996) observing stations to investigate the internal structure and dynamics of the Sun using helioseismology, the *Synoptic Optical Long-term Investigations of the Sun* (SOLIS, Keller, Harvey and Giampapa 2003) facility at Kitt Peak National Observatory (KPNO) in Arizona to study the solar activity cycle, the two *Precision Solar Photometric Telescopes* (PSPTs, Coulter and Kuhn 1994) at Mauna Loa Solar Observatory (MLSO) on the Big Island of Hawai'i and Osservatorio Astronomico di Roma (OAR) in Italy to monitor solar irradiance changes, and the *Optical Solar Patrol Network* (OSPAN), formerly known as the *Improved Solar Observing Optical Network* (ISOON, Neidig *et al.* 1998), to monitor solar eruptive events. Finally, a meter-class coronagraph has been proposed by the High-Altitude Observatory (HAO) of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. The *Coronal Solar Magnetism Observatory* (COSMO, Tomczyk, Lin, and Zurbuchen 2007) would replace existing MLSO facilities.

Astronomical seeing conditions at *Dome C* are exceptional (Lawrence *et al.* 2004) and very promising for solar research. However, any new solar project has to establish a compelling science case, which exploits the unique seeing characteristics of the Antarctic plateau and which is competitive in this highly active research environment.

2   Daytime Seeing Characteristics at Dome C

The French/Italian *Concordia* station at *Dome C* is located on the Antarctic plateau (75°6′ South and 123°21′ East) at an elevation of 3250 m. Aristidi *et al.* (2005) carried out a rigorous study of the daytime seeing characteristics at this site. The data were obtained with a differential image motion monitor (DIMM, *e.g.*, Sarazin and Roddier 1990) during two 3-months campaigns during the Antarctic summers of 2003–2004 and 2004–2005. They measured a median seeing of $0.54''$ and a medium isoplanatic angle of $6.8''$, which indicate excellent seeing conditions. The seeing was typically even better for several hours during the afternoon ($\approx 0.4''$ corresponding to a Fried-parameter $r_0 \simeq 25.0$ cm at 500 nm). However, the Antarctic daytime seeing measurements were based an observations of the bright star Canopus and the aforementioned results have been zenith angle corrected, which is not suitable evaluating the potential for solar observations. Therefore, the seeing statistics have to be reevaluated for solar observations and interpreted in the light of a specific science case.

Seeing with a Fried-parameter better than $r_0 \gtrsim 7.0$ cm marks the threshold at which wavefront sensors can lock on granulation as a target and solar adaptive optics (AO) systems can operate (Rimmele 2000). The excellent seeing regime starts with Fried-parameters $r_0 \gtrsim 12.0$ cm. This enables high spectral resolution observations, which require long exposure times (in excess of the daytime coherence time $t_{exp} \gtrsim \tau_0 \approx 40.0$ ms). Good time coverage is required to follow the evolution of three-dimensional flow and magnetic fields in active regions. An interesting statistical property is the number of hour blocks when the seeing continuously exceeds the thresholds of $r_0 = 7.0$ and 12.0 cm, respectively. Anecdotal evidence is presented in Aristidi *et al.* (2005) who report exceptional seeing as low as $0.1''$ during a 10-hour continuous period of seeing below $0.6''$.

Concordia station provides a range of seeing characteristics, which are attractive for solar observations: The large clear time fraction (CTF) of at least 75% during the three

months of Antarctic summer promises about 1,600 hours of observations. This is about 60% of the total observing time of low/mid-latitude solar observatories, which observe the whole year. However, it might well be, if the hour block statistics for the $r_0 = 7.0$ and 12.0 cm thresholds are carried out, that *Concordia* station outperforms other solar sites. The final report of the ATST site survey working group could serve as a benchmark (Hill *et al.* 2004). During the Antarctic summer, the Sun "oscillates" above the horizon, providing long continuous time sequences, without interruptions due to the day-night cycle. This is a unique property, which can otherwise only be achieved from space.

The excellent seeing conditions (large Fried-parameter, large isoplanatic angle, and long atmospheric coherence time) are advantageous for high spatial resolution observations. However, synoptic full-disk observations would also benefit, since the normalized Fried-parameter $\alpha = r_0/D$, where $D \approx 25.0$ cm is the telescope diameter, would be close to unity. Furthermore, low-order wavefront correction facilitated by ground-layer adaptive optics (GLAO, Tokovinin 2004) might become feasible. Aristidi *et al.* (2005) find that almost half of the ground turbulence is concentrated into the first 5.0 m above the surface. The performance of a GLAO system is not a strong function of the field of view (FOV). Since low-altitude aberrations are isoplanatic (Tokovinin 2004), only a thin layer has to be corrected at *Dome C*. Thus, a large field can be compensated. A wide-field GLAO system with a $5'$ FOV has been proposed for the *Gemini* telescopes (Andersen *et al.* 2006).

Finally, the extremely cold and dry air, very low infrared sky emission, and low aerosol and dust content will offer some of the best coronal skies (Lawrence *et al.* 2004, Kenyon and Storey 2006). Efforts are currently underway, to quantify the site characteristics for coronal observations.

3   Advanced Solar Photometric Imager and Radiation Experiment

The envisioned *Advanced Solar Photometric Imager and Radiation Experiment* (ASPIRE) is an innovative photometric full-disk telescope to explore the solar photosphere and chromosphere in the blue spectral region. ASPIRE could share the same mount and use the infrastructures of the *International Concordia Explorer Telescope* (ICE-T), thus, leveraging the investments in ICE-T by adding a daytime science component. The ASPIRE concept is well adapted to the seeing conditions at *Dome C* and relates to a variety of promising science cases. The blue end of the visible spectrum contains a variety of interesting spectral features (see Fig. 1). Smart coatings on the entrance window will restrict the transmitted sunlight to 380–460 nm. Thus, only 10% of the solar radiant energy will enter the instrument, which is less than 10 W. Thermal loads on optical elements are not critical but an evacuated or helium filled telescope tube has to be considered to avoid instrument seeing. Relatively wide (≈ 1.0 nm) interference filters can be used to isolate these spectral regions, thus, enabling photometric tomography (height dependence) of small-scale magnetic features.

The key idea of ASPIRE is to combine synoptic observations with high spatial resolution. In addition, ASPIRE data will be obtained with high temporal resolution (one image per spectral region every 30 s) as well as a low scattered light level and very good photometric accuracy (better than 0.1%). As part of ICE-T, large-format detectors with 10k
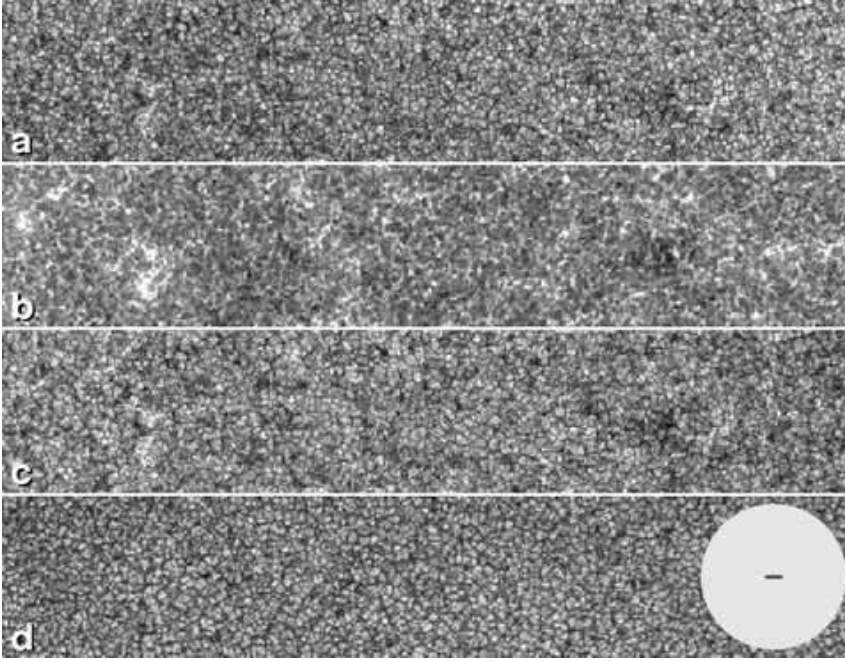
Fig. 1. Quiet Sun observations obtained with the Broadband Filter Imager (BFI) of the *Solar Optical Telescope* (SOT) on board *Hinode*(Kosugi *et al.* 2007) on 2007 September 5. The filtergrams were taken quasi-simultaneously in **a** the CN bandhead (388.4 nm), **b** the strong chromospheric absorption line Ca II H (396.9 nm), **c** the G-band (430.5 nm), and **d** the blue continuum (450.5 nm), respectively. The FOV is $220'' \times 42''$. About nine of these image stripes have to be assembled to cover the entire solar equator. The insert in the corner provides a comparison of the solar disk with the high-resolution FOV.

$\times$ 10k pixels will become available for daytime observations. Full-disk filtergrams would have an image scale of $0.2''$ pixel^{-1} with such detectors. Considering the excellent seeing conditions at *Dome C*, telescopes with small apertures (≈ 25.0 cm) could obtain images with a spatial resolution better than $0.5''$ during substantial periods of time. Assuming an exposure time of 10 ms, a bandpass of 1.0 nm and a total wavelength-dependent system efficiency of 2.5–3.3%, the photon statistics ($n > 200,000$) would be well adapted to the full well capacity of the CCD and still leave some latitude in filter specifications and observing procedures. Short exposure times are necessary to allow for post-facto image restoration in addition to real-time GLAO correction. A small number of filtergrams (3–10) is sufficient for multi-frame blind deconvolution (MFBD) techniques (*e.g.*, van Noort, Rouppe van der Voort, and Löfdahl 2005).

In Fig. 2, we show a comparison of the spatial resolution, which can be achieved with *Hinode* SOT, ASPIRE, and the *Precision Solar Photometric Telescope* (PSPT, Coulter and Kuhn 1994). The image scales of these instruments are 0.054, 0.2, and $1.0''$ pixel^{-1},
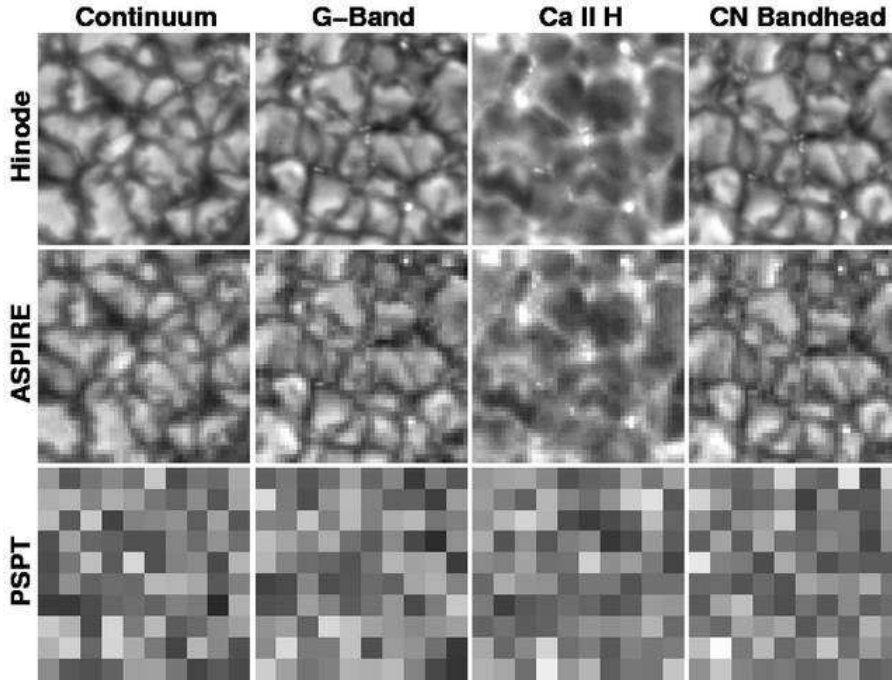
Fig. 2. Comparison of the spatial resolving power between *Hinode* SOT, ASPIRE, and PSPT for different spectral regions. The FOV is $10'' \times 10''$.

respectively. We degraded the *Hinode* SOT data to match the image scale of the other instruments. The resolving power of ASPIRE is sufficient to resolve solar granulation and even small-scale bright points are still detectable. Therefore, photospheric and chromospheric optical flows can be measured, *i.e.*, horizontal proper motions, across the entire disk. Furthermore, feature identification and pattern recognition techniques can be applied to the filtergrams. These capabilities are currently not available from any other synoptic telescope.

High spatial and temporal resolution come at a price. A single 16-bit image is about 200 MB, which results in a data rate of 1.6 GB min^{-1}. About 250 TB data would be collected over one Antarctic summer. This huge amount of data might be hard to handle. We intend to save one filtergram per spectral region with full spatial resolution every 30 min. This would result in a total of about 2 TB of data (with lossless compression). High cadence observations are primarily required for local correlation and feature tracking to measure the optical flows (*e.g.*, November and Simon 1988, Roudier *et al.* 1999). In this case, photometric accuracy can be sacrificed and lossy compression algorithms can be used. The data amount with full spatial and temporal resolution would be in this case only 25 TB. In summary, depending on the scientific objective observing modes can be selected, which fit the data storage and analysis limitations.

4   Science Cases for Synoptic Solar Observations

4.1   Differential Rotation, Meridional Flows, and Large-Scale Flow Patterns

Horizontal proper motions can be detected as optical flows using local correlation or feature tracking algorithms. The final resolution of the velocity maps will match *Helioseismic and Magnetic Imager* (HMI) data, which will become available in August 2008 with the launch of the *Solar Dynamics Observatory* (SDO, Kosovichev *et al.* 2007). The flow field contains contributions from solar differential rotation, meridional flows, and localized flow patterns due to active regions evolution and flux emergence. Seeing will introduce a noise term so that between 50 and 100 filtergrams are needed for one flow map. Photometric tomography then provides the height dependence of the flow fields. The transition from differential surface rotation to the more rigid rotation of the corona is one topic, which can be addressed with ASPIRE. Coronal hole regions are of particular interest and UV/EUV filtergrams obtained with the SDO's *Atmospheric Imaging Assembly* (AIA) can provide the coronal context. Since the velocity signal (300–500 m s^{-1}) of supergranulation is mostly horizontal, ASPIRE would be ideal to study large scale convective patterns and giant cells. These convective motions can than be related to the Ca II K network and other features associated with the Sun's ubiquitous magnetic field.

The solar surface is highly dynamic, and magnetic fields on various spatial scales, from active regions and sunspots to network fields and faculae, are intricately intertwined with plasma motions. Photospheric flows can contribute to the build-up of magnetic shear in active regions, which will store energy in the complex three-dimensional magnetic field topology above active regions. This energy can be violently released in flares, filament and prominence eruptions, and coronal mass ejections (CMEs). The importance of plasma flows associated with solar eruptive events was recently demonstrated by Yang *et al.* (2004). ASPIRE's global coverage will help to monitor flow patterns in active regions, which might become source regions for solar eruptive events.

4.2   Solar-Terrestrial Relations

The total radiative energy arriving at Earth is known as the solar "constant" $S = 1366 \pm 3$ W m^{-2}. On the other hand, solar activity has a pronounced 11-year cycle which manifests itself in the radio flux, the X-ray background, the UV/EUV and total irradiance and the frequency of various solar features such as sunspots, plages, filaments, prominences, flares, CMEs, and coronal holes. The common source for solar variability is the Sun's magnetic field. Analyzing the magnetic field data reveals that the magnetic cycle is actually 22 years, switching from a North-South to a South-North configuration and back. This apparent dichotomy between constancy and variability makes the radiative coupling of the Sun-Earth system an intriguing field of research. Especially, since solar irradiance variability has been related to global climate change on Earth and the discussion of its importance compared to anthropogenic effects. The UV and EUV show the strongest irradiance variations. Faculae and plages are particularly strong emitters in this specific wavelength region. Furthermore, UV/EUV radiation plays an important role in the energy balance and chemistry of Earth's upper atmospheric layers, *e.g.*, the dissociation of ozone

by UV photons in the range of 200 to 300 nm. Ca II K filtergrams provide an important proxy for the UV/EUV variability. A detailed review of solar irradiance variability and solarterrestrial effects was given by Lean (1997) and more recently by Fröhlich and Lean (2004).

Feature identification and pattern recognition can be used to discriminate between plages, faculae, network and sunspots and thus measure their contribution to irradiance variability. Brightness temperatures are accessible with multi-color photometry and the flux tube geometry can be mapped in height by studying the center-to-limb variation of faculae, pores, plages, and filigree. This structural analysis will be complemented by high resolution HMI vector magnetograms. ASPIRE is envisioned as a pathfinder for solar observations at *Dome C*. However, its contributions towards solar cycle variations are significant, which could warrant an extension of the project and justify funding to cover an entire solar cycle.

4.3   Solar-Stellar Connection

ICE-T is a twin 60-cm aperture telescope for Sloan *g* and *i* photometry (Strassmeier *et al.* 2007, 2008). Precision wide-field photometry is the common denominator of ICE-T and ASPIRE enabling synergies in instrumentation, IT infrastructure and data analysis. Beyond the instrumentation aspects, common ground can be found for a variety of science cases such as (stellar) differential rotation, magnetic activity of late-type stars, and dynamo activity. ASPIRE is in this respect a Sun-as-a-Star telescope but with unprecedented spatial resolution.

Themes of the solar-stellar connection (Cayrel de Strobel 1996) include magnetic cycles of activity and their evolution, atmospheric structure(s), heating processes, abundances, and the presence of planets around cool stars other than the Sun (see *e.g.*, Dupree 2003). *ASPIRE* will measures globally horizontal proper motions, thus, providing information on (1) differential rotation, which converts poloidal to toroidal fields, (2) meridional flows at the solar surface, which transport flux towards poles, and (3) convective surface patterns, which lead to diffusion of the magnetic field. More and more details of these solar dynamo signatures are now being extracted from and discovered in stellar observations as well (see *e.g.*, Strassmeier 2005). Combining highly resolved "snapshots" of solar activity with observations of solar-type stars at various evolutionary stages demands models, which integrate these diverse data sets to answer a variety of fundamental questions: How does the dynamo evolve over the life-time of a star and how is it related to spin down and angular momentum transport by stellar winds? How often do Maunder minimum events occur? What is the relationship between differential rotation and rotation rate? Do counterparts to solar activity nests and active longitudes exists and how do they affect the structure of stellar coronae?

Finally, the emerging field of *space climate* (Nandy and Martens 2007) embraces the topics of solar-terrestrial relations and solar-stellar connection. Modulation of the magnetic, radiative and particle environment in the heliosphere is of great importance for star-planet interactions in the habitable zone over stellar evolution time scales. Magnetic activity changes as the dynamo evolves during the stars lifespan, thus, forcing planetary systems – which respond. The details of such an interaction of course pique the human

curiosity, since they are closely tied to the question of the origin of life on Earth and possibly on other planets.

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